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The Galactic Double-Neutron-Star Merger Rate: Most Current Estimates

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Abstract. We summarize our results on the Galactic merger rate of double neutron stars (DNS) in view of the recent discovery of PSR J0737−3039. We also present previously unpublished results for the *global* probability distribution of merger rate values that incorporate the presently known systematics from the radio pulsar luminosity function. The most likely value obtained from the global distribution is only $\simeq 15\,\mathrm{Myr}^{-1}$, but a re-analysis of the current pulsar sample and radio luminosities is needed for a reliable assessment of the best fitting distribution. Finally, we use our theoretical understanding of DNS formation to calculate a possible upper limit on the DNS merger rate from current Type Ib/c supernova rate estimates.

1. Introduction

Soon after the discovery of the highly relativistic pulsar J0737−3039 (Burgay et al. 2004) we applied our analysis method for pulsar populations and calculated the updated merger rate estimates for the current sample of Galactic close DNS (Kalogera et al. 2004). Our main conclusion was that this new, remarkably relativistic system is very significant for these estimates and leads to a rate increase by a factor of 5−7. This implies a correspondingly significant increase in DNS inspiral event rates for gravitational-wave (GW) interferometers like LIGO. In what follows, we summarize our recent results and present new results on: (i) how a *global* probability distribution of rate estimates can be calculated with the systematic uncertainties; (ii) the possible upper limits that could be imposed on the DNS merger rate if we adopt the theoretically expected relationship between DNS merger rates and Type Ib/c supernova (SN) rates.

2. The revised Galactic DNS merger rate

In Kim, Kalogera, & Lorimer (2003; hereafter KKL), we introduced a statistical method to calculate the probability density function (PDF) of the rate estimates for Galactic close DNS. After the discovery of PSR J0737−3039, we derived a

combined $P(\mathcal{R})$ considering the three observed DNS systems in the Galactic disk (for details see Appendix A of Kim et al. 2004).

To calculate the merger rate of DNS systems in our Galaxy, we need to estimate: (i) the number $N_{\rm tot}$ of Galactic pulsars with pulse and orbital characteristics *similar* to those in the observed sample; (ii) the lifetime $\tau_{\rm life}$ of each observed system; (iii) an upward correction factor $f_{\rm b}$ for pulsar beaming.

We calculate $N_{\rm tot}$ by modeling in detail the pulsar-survey selection effects for a number of pulsar population models described in KKL. The model assumptions for the pulsar luminosity function dominate the systematic uncertainties of our overall calculation.

The lifetime of the system is defined by $\tau_{\rm life} \equiv \tau_{\rm sd} + \tau_{\rm mrg}$, where $\tau_{\rm sd}$ is a spin-down age of a recycled pulsar (Arzoumanian, Cordes, & Wasserman 1999) and $\tau_{\rm mrg}$ is the remaining lifetime until the two neutron stars merge (Peters & Mathews 1963). We note that the lifetime of J0737−3039 is estimated to be 185 Myr, which is the shortest among the observed systems.

The beaming correction factor $f_{\rm b}$ is defined as the inverse of the fractional solid angle subtended by the pulsar beam. Its calculation requires detailed geometrical information on the beam. Following Kalogera et al. (2001), we adopt $f_{\rm b} = 5.72$ for PSR B1913+16 (Hulse & Taylor 1975) and 6.45 for PSR B1534+12 (Wolszczan 1991). Without good knowledge of the geometry of J0737−3039A, we adopt the average value of the other two systems ($\simeq 6.1$).

In Figure 1, we show $P(\mathcal{R})$ for our chosen reference model that allows for a low minimum pulsar luminosity (Model 6 in KKL). The most likely value of $\mathcal{R}$ turns out to be $83\,{\rm Myr}^{-1}$, larger by a factor of $\simeq 6.4$ than the rate estimated before the discovery of J0737−3039. We find the same increase factor for all pulsar population models examined. This revised merger rate implies an increase in the detection rate of DNS inspirals for ground-based GW interferometers such as LIGO (Abramovici et al. 1992). Using the standard extrapolation of our reference model out to extragalactic distances (see Kalogera et al. 2001), we find that the most probable event rates are 1 per 29 yrs and 1 per 2 days, for initial and advanced LIGO, respectively. At the 95% confidence interval, the most optimistic predictions for the reference model are 1 event per 8 yrs and 2 events per day for initial and advanced LIGO, respectively. For more details see Kalogera et al. (2004).

The revised DNS merger rate is dominated by PSR J0737−3039. Therefore, if the estimated lifetime of this system is revised in the future, it will directly affect our rate estimation. Lorimer et al. (in this volume) calculated the spin-down age of the system with various spin-down models and suggested an age in the range 30–70 Myr, which is shorter than the value we adopted for our calculation ($\tau_{\rm sd}$ =100 Myr). The edges of this range give us rate estimates of $\mathcal{R} \simeq 90 - 115\,{\rm Myr}^{-1}$.

The beaming correction for J0737−3039 is also important for our rate estimation. Recently, Jenet & Ransom (2004) suggested a geometrical model for this newly discovered system. According to their model, the predicted beaming correction factor is $\geq$6 assuming a two-sided beam (Jenet 2004, private communication). If confirmed, this could lead to a further dramatic increase in the merger rate estimates.

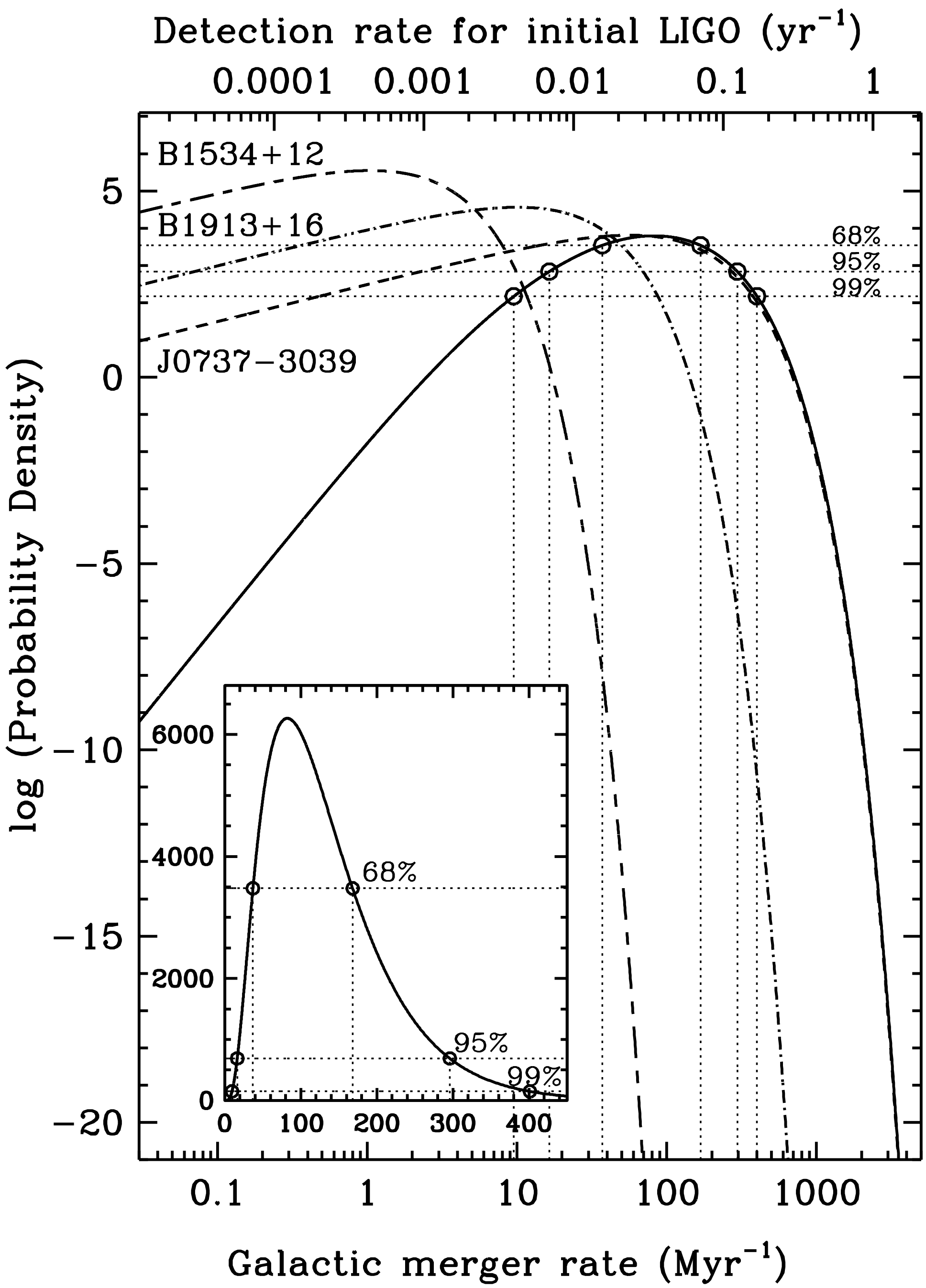

Figure 1. The PDF of DNS merger rate $P(\mathcal{R})$ is shown on a log scale. The thick solid line is the total Galactic rate estimate overlapped with results for individual observed systems (dashed lines). Dotted lines indicate confidence intervals for the rate estimates. The same results are shown on a linear scale in the small inset. All results shown are for our reference model.

3. Global probability distribution of the rate estimates

In KKL, we showed that estimated Galactic DNS merger rates are strongly dependent on the assumed luminosity distribution function for pulsars. So far, we have reported results for each set of population model assumptions. Here we describe how we can incorporate the systematic uncertainties from these models and calculate, $P_{\rm g}(\mathcal{R})$, a *global* PDF of rate estimates. However, we stress that the information needed for such a calculation is currently not up to date; therefore, specific quantitative results could change when constraints on the luminosity function are derived from the current pulsar sample.

We calculate $P_{\rm g}(\mathcal{R})$ using the prior distributions of the two model parameters for the pulsar luminosity function: the cut-off luminosity $L_{\rm min}$ and power-index p. We calculate these priors by fitting the marginal PDFs of $L_{\rm min}$ and p presented by Cordes & Chernoff (1997). We obtain the following analytic formulae for $f(L_{\rm min})$ and $g(p)$: $f(L_{\rm min}) = \alpha_0 + \alpha_1 L_{\rm min} + \alpha_2 L_{\rm min}^2$ and $g(p) = 10^{\beta_0+\beta_1 p+\beta_2 p^2}$, where $\alpha_{\rm i}$ and $\beta_{\rm i}$ (i $= 0, 1, 2$) are coefficients we obtain from the least-square fits and the functions are defined over the intervals $L_{\rm min} = [0.0,\ 1.7]$ mJy kpc^2 and $p = [1.4,\ 2.6]$. We note that, although Cordes and Chernoff (1997) obtained $f(L_{\rm min})$ over $L_{\rm min} \simeq [0.3,\ 2]$ mJy kpc^2 centered at 1.1 mJy kpc^2, we consider $f(L_{\rm min})$ with a peak at ~ 0.8 mJy kpc^2 considering the discoveries of faint pulsars with L_{1400} below 1 mJy kpc^2 (Camilo 2003).

We use the above priors to calculate $P_{\rm g}(\mathcal{R})$:

$$P_{\rm g}(\mathcal{R}) = \int_p dp \int_{L_{\rm min}} dL_{\rm min} P(R) f(L_{\rm min}) g(p)\ . \tag{1}$$

In Figure 2, we show the distributions of $L_{\rm min}$ and p adopted (top panels) and the resulting global distribution of Galactic DNS merger rate estimates (bottom panel). We find that $P_{\rm g}(\mathcal{R})$ is strongly peaked at *only* around $15\,{\rm Myr}^{-1}$. We note that this is a factor $\simeq 5.5$ smaller than the revised rate from the reference model ($\mathcal{R}$ $=83\,{\rm Myr}^{-1}$). At the 95% confidence interval, we find that the Galactic DNS merger rates lie in the range ~ 1–$170\,{\rm Myr}^{-1}$. These imply LIGO event rates in the range $\sim (0.4-70)\times 10^{-3}\,{\rm yr}^{-1}$ (initial) and $\sim 2-380\,{\rm yr}^{-1}$ (advanced). Given these implications, it is clear that up-to-date constraints on $L_{\rm min}$ and p and their PDFs (a follow-up on Cordes & Chernoff 1997) are urgently needed.

4. Rate constraints from Type Ib/c supernovae and binary evolution models

Based on our current understanding of DNS formation, the progenitor of the second neutron star is expected to form during a Type Ib/c supernova. Therefore, the empirical estimates for the Type Ib/c SN rate in our Galaxy can be used to provide upper limits on the DNS merger rate estimates. From Cappellaro, Evans, & Turatto (1999) we adopt $\mathcal{R}_{\rm SN\,Ib/c} \simeq 1100 \pm 500\,{\rm Myr}^{-1}$ (for Sbc–Sd galaxies). Here, we assume $H_0 = 71\,{\rm km/s/Mpc}$ and $L_{\rm B,gal} = 9\times 10^9\,L_{\rm B,sun}$.

In order to find the fraction of SN Ib/c actually involved in the formation of DNS, we have examined population synthesis models calculated with the code `StarTrack` (Belczynski, Kalogera, & Bulik 2002; Belczynski et al. 2004)

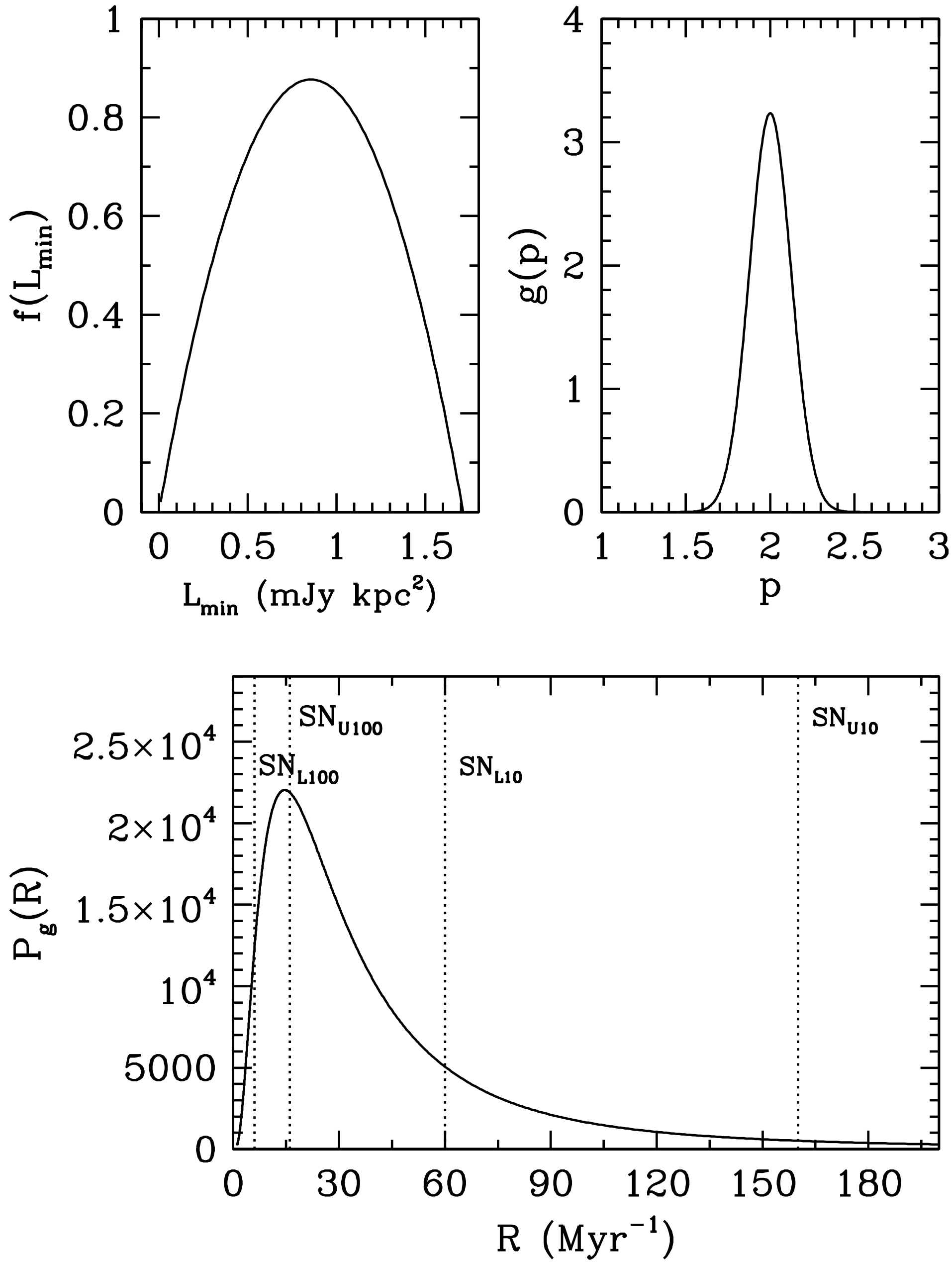

Figure 2. The global $P_{\rm g}(\mathcal{R})$ on a linear scale (lower panel) and the assumed intrinsic distributions for $L_{\rm min}$ and p (upper panels). Dotted lines represent the lower ($SN_{\rm L}$) and upper ($SN_{\rm U}$) bounds on the observed SN Ib/c rate scaled by 1/10 and 1/100 (see text). The empirical SN Ib/c rates range over $\sim 600 - 1600\,{\rm Myr}^{-1}$, where the average is at $\sim$1100 ${\rm Myr}^{-1}$ (Cappellaro, Evans, & Turatto 1999), beyond the range shown here.

and find very low rate ratios: $\gamma \equiv \mathcal{R}/\mathcal{R}_{\rm SN\,Ib/c} \sim 0.001-0.005$. Several models with He-star winds consistent with current observations (weaker than previously thought) lead to $\gamma \simeq 0.005$. We note that systematic overestimation of $\mathcal{R}_{\rm SN\,Ib/c}$ relative to SN II rates has already been pointed out (Belczynski, Kalogera, & Bulik 2002; this is related to the assumption of *complete* removal of H-rich envelopes). However, we find that this discrepancy would raise the value of γ by just a factor of a few. As an approximate constraint, we adopt the empirical $\mathcal{R}_{\rm SN\,Ib/c}$ and scale it by 1/10 and 1/100, reflecting the results from population synthesis calculations. We overlay these scaled values in Fig. 2 (dotted lines in the bottom panel) using the ranges for SN Ib/c reported by Cappellaro, Evans, & Turatto (1999).

We note that our most optimistic DNS merger rate is $\mathcal{R} = 224^{+594}_{-181}$ Myr^{-1} at a 95% confidence interval (Model 15 in KKL). We obtain γ for SN Type Ib/c to be $\sim$0.8 with the upper limit of $\mathcal{R}$ at the 95% confidence interval. This corresponds to γ $\sim$0.1 with a SN Type II rate, which is factor 6.1 larger than that of SN Type Ib/c. In both cases, the most optimistic model is lower than the current empirical supernova rate estimates, but not really consistent with the results of population synthesis calculations. If we consider the global distribution, with the upper limit of $\mathcal{R}$ at the 95% confidence interval, we obtain γ $\sim$0.15 and 0.025 for SN Type Ib/c and II, respectively.

5. Prediction for more DNS detections by the PMB survey

Acceleration searches of the PMB-survey data (Faulkner et al. 2003) should significantly improve the detection efficiency of DNS binaries. Although the data analysis is on-going, acceleration searches already led to the discovery of PSR J1756−2251 (see Faulkner et al. 2004 and the contribition by Lyne in this volume).

Following the method described in Kalogera, Kim & Lorimer (2003), we calculate the probability to detect a pulsar similar to any of the observed DNS systems. We assume that acceleration searches can perfectly correct for the reduction in flux due to Doppler smearing, namely no degradation in the calculation of signal-to-noise ratio for the PMB survey is included. Considering observed DNS systems individually, we calculate the expected number of pulsars to be detected by the PMB survey ($N_{\rm exp}$).

The probability distribution of $N^i_{\rm exp}$ for each DNS pulsar sub-population i (B1913+16, B1534+12, J0737–3039) is given by:

$$P_i(N_{\rm exp}) = \frac{{\beta_i}^2}{(1+\beta_i)^2}\frac{(N_{\rm exp}+1)}{(1+\beta_i)^{N_{\rm exp}}}\ , \tag{2}$$

where the constants β_i are a measure of how less likely it is to detect pulsars without acceleration searches relative to with acceleration searches. For each sub-population, we calculate the mean values of $N_{\rm exp}$, which are $\bar{N}_{\rm exp,1913} = 0.9$, $\bar{N}_{\rm exp,1534} = 1.2$, and $\bar{N}_{\rm exp,0737} = 1.9$.

The increase of the observed sample is very important for the reduction of the uncertainties associated with the DNS merger rate estimates. We note, however, that the discovery of new systems that are *similar* to the three already

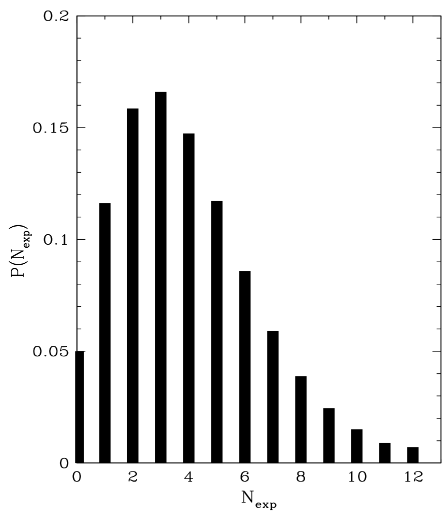

Figure 3. $P(N_{\rm exp})$ for close DNS systems in the PMB survey. We consider all three observed systems in the Galactic disk. The mean value is $\bar{N}_{\rm exp}$ =4.0. The result shown here is based on our reference model.

known does not necessarily imply a significant increase in the rate estimates. Significant changes are expected when new systems are discovered with pulse profiles or binary properties significantly different than the old ones, as those systems will reveal a new DNS sub-population in the Galaxy.

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